# Polyhydroxyalkanoates (PHAs): Mechanistic Insights and Contributions to Sustainable Practices

Subjects: Chemistry, Medicinal

Contributor: Sushobhan Pradhan , Mohd Tauhid Khan , Vijayanand S. Moholkar

A polymer is a long-chain molecule formed by linking numerous simpler repeating chemical units, known as monomers, with identical structures. Over the past two centuries, there has been a significant increase in the global production and use of petrochemical-based plastics. This surge has led to widespread ecological imbalances, affecting air quality, terrestrial and marine ecosystems, food chains, and plant life. Consequently, the excessive use of such polymers has created challenges in solid waste management, with methods like bio- or photo-degradation, incineration, landfilling, and recycling proving to be time-consuming and laborious. Therefore, there is a growing urgency for biodegradable polymers due to increasing demand. Biodegradable polymers consist of interconnected monomers with unstable links in the backbone, facilitated by various functional groups. Throughout the degradation process of these polymers, numerous biologically acceptable molecules are produced. This study examines the significance of biopolymers over petroleum-based counterparts, offering a detailed analysis. It is noteworthy that within the spectrum of biodegradable polymers, polyhydroxyalkanoates (PHAs) emerge as exceptionally promising candidates for substituting petroleum-derived polymers, owing to their remarkable physical attributes. Therefore, this study provides a systematic overview of PHAs, including their classification, historical background, methods of production, potential challenges to commercialization, and diverse applications.

biopolymer polyhydroxyalkanoate microorganism biodegradation

### 1.1. Overview to Petroleum-Derived Polymers

A polymer is a long-chain macromolecule composed of the interlinking of a large number of simpler repeating chemical units, also referred to as monomers, with identical structures. The term “polymer” originates from classical Greek, where “poly” signifies “many” and “meres” denotes “parts”. This etymological foundation reflects the fundamental characteristic of polymers. Natural polymers, such as proteins, cellulose, resin, wool, and silk, occur in nature. Synthetic polymers, including polyethylene, polypropylene, polystyrene, polyvinyl chloride, and nylon, are produced through chemical synthesis. Some natural polymers, like natural rubber (polyisoprene) derived from the Hevea tree, can also be synthesized artificially [1][2].

Over the past two centuries, global production and utilization of petrochemical-based plastics have surged significantly, causing ecological imbalances across air quality, ecosystems, food chains, and plant life [3]. For instance, global plastic production rose from two million tons in 1950 to over 400 million tons by 2022 [4]. **Figure 1**a illustrates the growth of petroleum-derived plastics over this period.

Initially, the adoption of petroleum-based plastics, such as polyethylene and polypropylene, aimed to enhance quality of life and comfort. This was due to their superior thermal, mechanical, electrical, and optical properties compared to conventional materials, as well as their cost-effectiveness. However, their pervasive use has led to challenges in solid waste management, incineration, landfilling, and recycling, which are labor-intensive and time-consuming [5][6]. Hence, the necessity for biodegradable polymers has become increasingly pressing. According to European Bioplastics e.V. (Berlin, Germany), as of 2022, bioplastics account for approximately 0.5 percent of the more than 400 million tons of plastic produced annually [7].

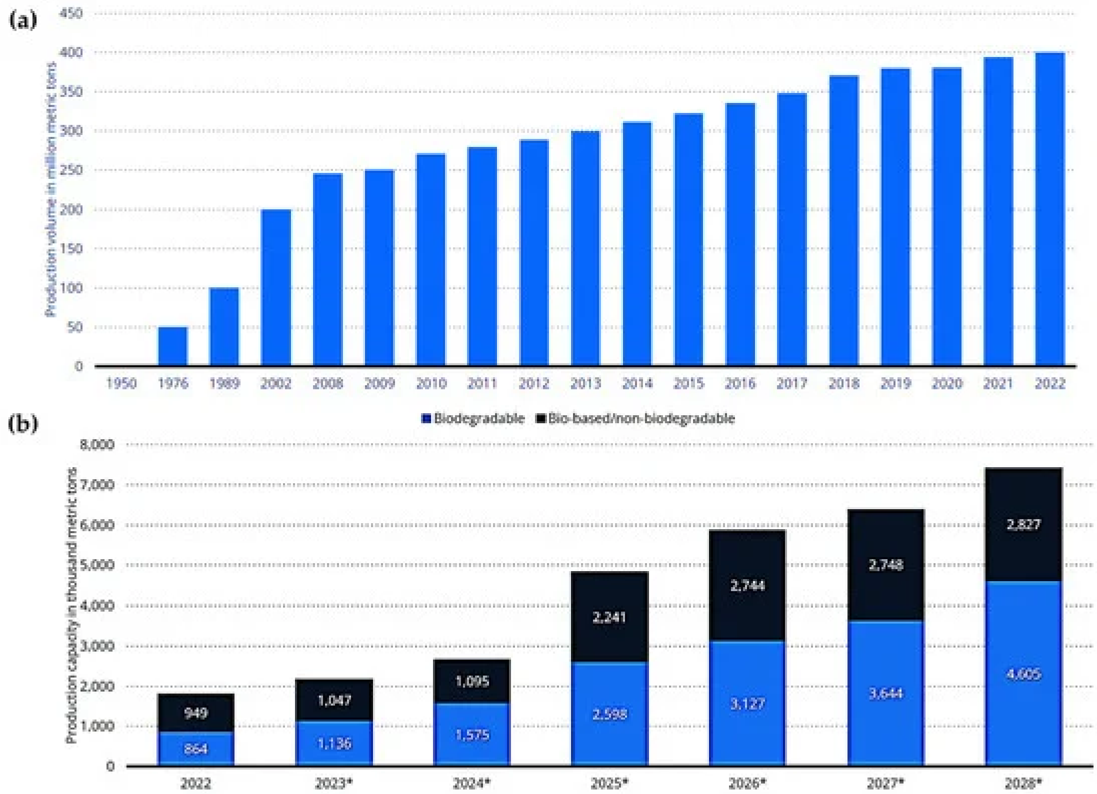


**Figure 1.** (**a**) Annual worldwide production of plastics from 1950 to 2022 (in million metric tons) and (**b**) production capacity of bioplastics globally from 2022 to 2028, categorized by type (in 1000 metric tons). * Figures from 2023 to 2028 are projections. Source: Statista—Bioplastic industry worldwide (2024) [8].

Based on data sourced from Statista, it has been revealed that the worldwide production capacity of bioplastics (biodegradable and bio-based/non-biodegradable) stood at 1.8 million tons in 2022. Current projections indicate an extraordinary trajectory for the industry, with anticipated growth leading to a production capacity of 7.5 million tons by 2028. This surge in bioplastic production capacity not only reflects a shift towards environmentally conscious practices but also signals a promising future for the bioplastics sector, poised to play a pivotal role in mitigating the environmental impacts associated with traditional plastics. **Figure 1**b encapsulates the production capacity of bioplastics in the year 2022 and the projections extending from 2023 to 2028 provide a glimpse into the anticipated growth trajectory of the bioplastics industry, highlighting its potential to meet the increasing demand for eco-friendly materials in a world increasingly focused on environmental sustainability [8].

### 1.2. Overview to Bio-Based Polymers

According to ASTM standard D-5488-94d [9], "biodegradable" refers to the capability of a substance to breakdown into biomass, carbon dioxide ($CO_2$), inorganic substances, methane ($CH_4$), water, or primarily through the enzymatic action of microorganisms. This process can be measured by standardized tests within a specified period, reflecting typical disposal conditions [9]. Biodegradable polymers are composed of monomers interconnected via unstable links in the backbone, facilitated by various functional groups. During the degradation process of these polymers, various biologically accepted molecules are formed [5]. Based on the synthesis process, biodegradable polymers can be categorized into four main types: those derived from biomass, polymers produced through microbial processes, polymers originating from monomers sourced from agricultural resources, and polymers synthesized through chemical methods [10][11]. A diagram depicting diverse categories of biodegradable polymers has been presented, accompanied by specific examples, as shown in **Figure 2**.

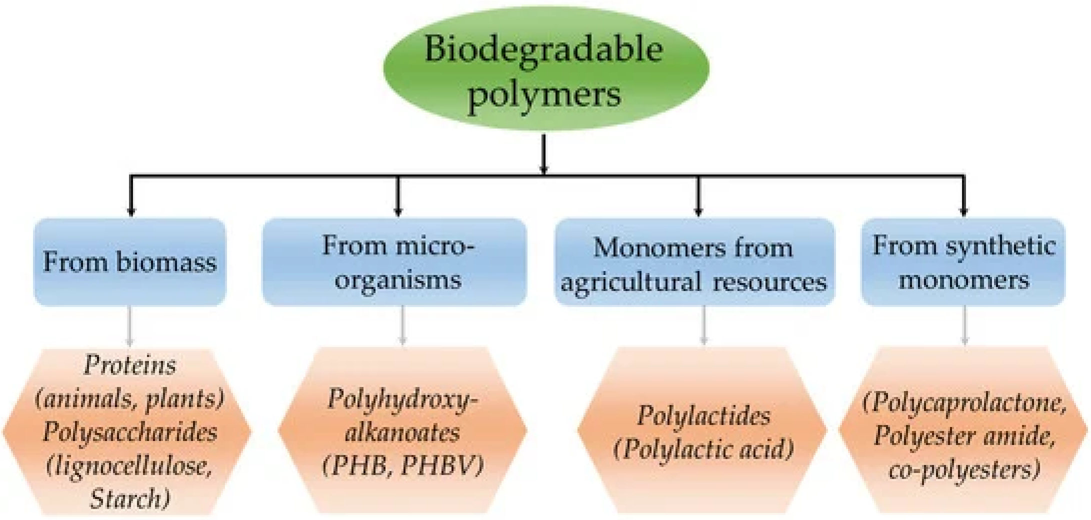


**Figure 2.** Classification of biodegradable polymers based on the synthesis process. Adapted with permission from ref. [12]. 2012 Springer Nature.

## References

1. Fried, J.R. Polymer Science and Technology; Pearson Education: London, UK, 2014.
2. Gowariker, V.R.; Viswanathan, N.; Sreedhar, J. Polymer Science; New Age International: Delhi, India, 1986.
3. de Paula, F.C.; de Paula, C.B.; Contiero, J. Prospective biodegradable plastics from biomass conversion processes. In Biofuels: State of Development; IntechOpen: London, UK, 2018; pp. 245–271.
4. Ritchie, H.; Samborska, V.; Roser, M.; Plastic Pollution. Our World in Data. 2023. Available online: https://ourworldindata.org/grapher/global-plastics-production (accessed on 16 October 2024).

5. Pradhan, S.; Dikshit, P.K.; Moholkar, V.S. Production, Characterization, and Applications of Biodegradable Polymer: Polyhydroxyalkanoates. In Advances in Sustainable Polymers; Springer: Singapore, 2020; pp. 51–94.
6. Khanna, S.; Srivastava, A.K. Recent advances in microbial polyhydroxyalkanoates. Process Biochem. 2005, 40, 607–619.
7. Bioplastics Market Development Update 2023; European Bioplastics e.V.: Berlin, Germany, 2023.
8. Bioplastic Industry Worldwide; Statistics Report on the Global Bioplastic Industry; Statista: Hamburg, Germany, 2024.
9. ASTM D5488-94de1; Standard Terminology of Environmental Labeling of Packaging Materials and Packages. ASTM International: West Conshohocken, PA, USA, 1994.
10. Averous, L. Biodegradable multiphase systems based on plasticized starch: A review. J. Macromol. Sci. Part C Polym. Rev. 2004, 44, 231–274.
11. Anne, B. Environmental-friendly biodegradable polymers and composites. In Integrated Waste Management; InTechOpen: London, UK, 2011; Volume I.
12. Avérous, L.; Pollet, E. Biodegradable polymers. In Environmental Silicate Nano-Biocomposites; Springer: Berlin/Heidelberg, Germany, 2012; pp. 13–39.